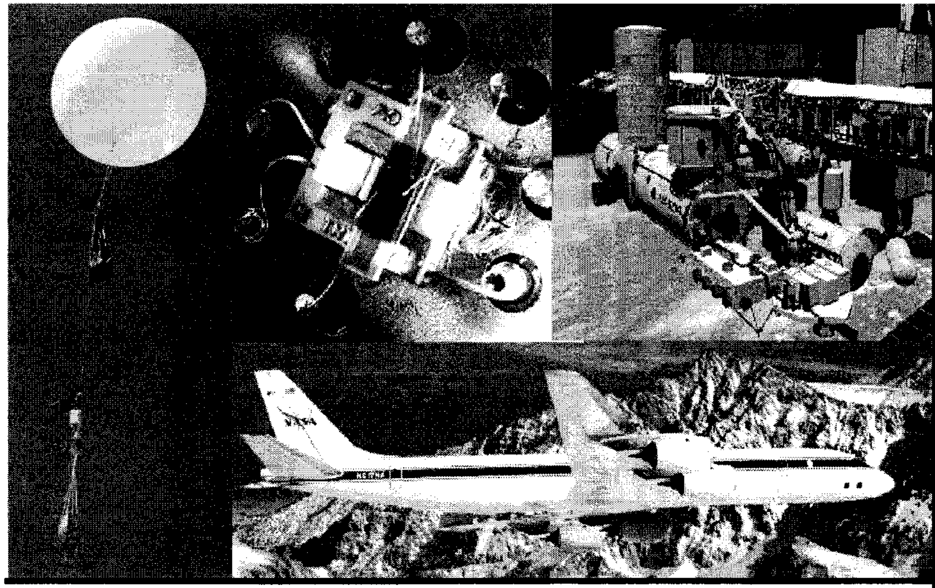
A Miniature Dewpoint Hygrometer for Monitoring Human Environments in Space

M. E. Hoenk, G. Cardell, F. Noca, and R. K. Watson

SAW Hygrometer for Environmental Monitoring



Task Purpose/Objectives:

To develop a reliable, handheld instrument suitable for fast, accurate measurements of local water vapor concentration in human environments in space.

Major Products:

Hand-held dewpoint hygrometer based on a surface acoustic wave device.

Sponsor: Advanced Environmental Monitoring Program, NASA Code UL

Period of Performance: 6/99 - 10/00

Saw hygrometer developed under funding from Codes Y, S.

Motivation:

Environmental control on the space station relies on circulation - high local concentrations of water vapor, in addition to posing a risk of condensation, are an indicator of stagnant air.

Humidity Measurement Technology

Technique	Comments
• Gravimetric	NIST standard
• Electrolytic – Saturated salt *(e.g., LiCl)* – Electrolysis *(P_2O_5)*	Older technology used in radiosondes
• Hygroscopic *(e.g., hygristor, humicap)*	Most widely used technology - low cost, currently used in radiosondes
• Capacitive (Al_2O_3)	Moderate cost, large range - damaged by high humidity
• Psychrometer	Primary measurement - limited dynamic range
• Condensation *(e.g., chilled mirror)*	Widely used where accuracy and wide dynamic range are important
• Optical – UV *(e.g., Lyman alpha hygrometer)* – Infrared *(e.g., TDL hygrometer)*	Fast, sensitive, accurate - often used in research aircraft
• Remote Sensing – RF radiometers – DIAL LIDAR – GPS occultation	Important for global coverage - requires ground truth validation / calibration

In Situ Humidity Sensors

Requirements

- **Small, low power sensor.**
- **Dynamic range - water concentration from parts per million to over 4%.**
- **Focus on technologies that are inherently accurate and easy to calibrate.**

Limitations of conventional technology:

Technology	**Solid State**	**Optical Absorption**
Principle	Water adsorption / absorption; Detect change in electronic properties: resistivity, dielectric constant, etc.	Optical absorption – Lyman α wavelength – Near IR region
Advantages	Compact geometry, low power.	Uses water-specific spectroscopic lines.
Disadvantages	Calibration drift (contamination, aging, hysteresis), Limited range (20-80%RH), poor accuracy (±5%RH) Temperature sensitive.	Calibration critical. Requires expensive laser and optics.

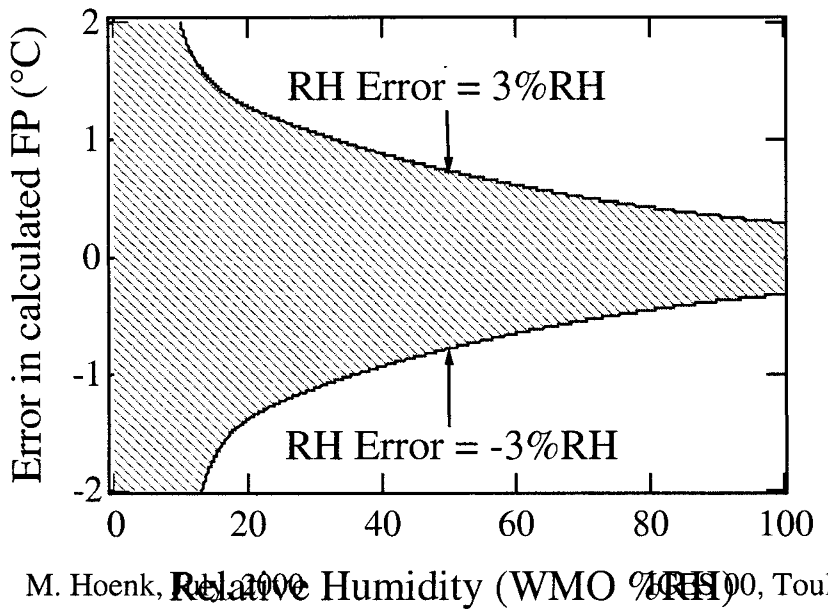
Technology	**Dewpoint hygrometers**
Principle	Detect dewpoint by observing condensation on chilled mirror surface. Detect light scattering induced by condensation.
Advantages	Direct measurement of thermodynamic quantity. Directly calibrated Non-hysteretic.
Disadvantages	Conventional instruments are massive and require high power. Slower response at low temperatures compared to optical hygrometers.

Relative Humidity Measurement

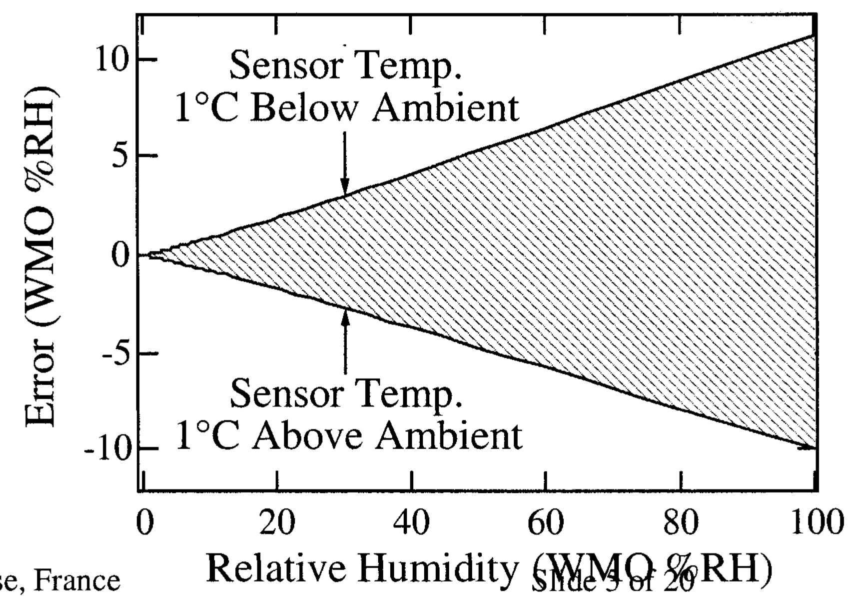
Principle: Material property (e.g., resistance) calibrated with respect to relative humidity (RH).

Problems with RH sensors:
- Calibration error
- Hysteresis and drift
- Poor response at low and high RH
- Sensitive to temperature

Uncertainty in Relative Humidity
Effect on Calculated Frostpoint
(at T_{amb} = 250 K)



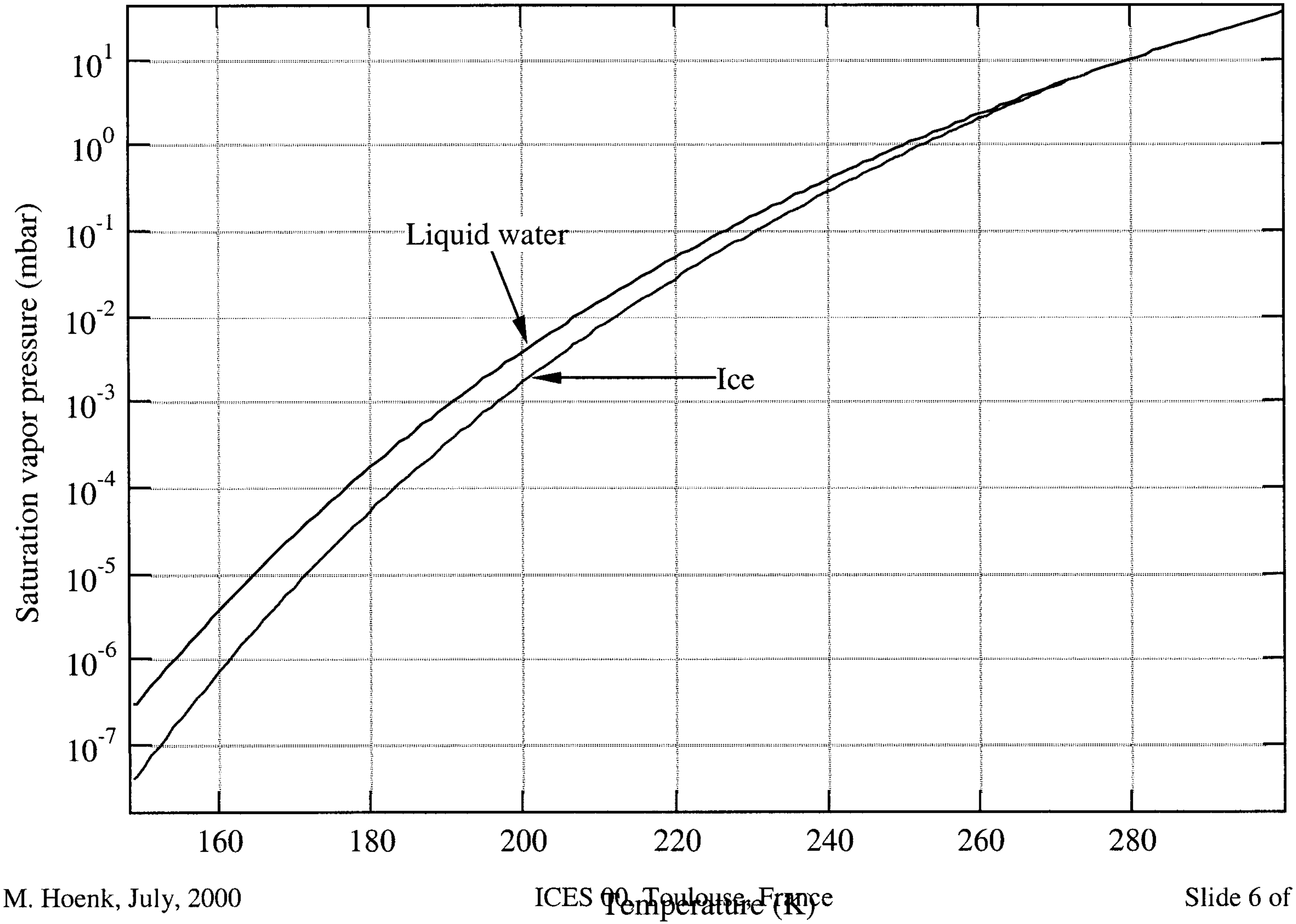
Uncertainty in Sensor Temperature
Effect on Measured RH
(at FP = -40°C)



Dewpoint Measurement of Humidity

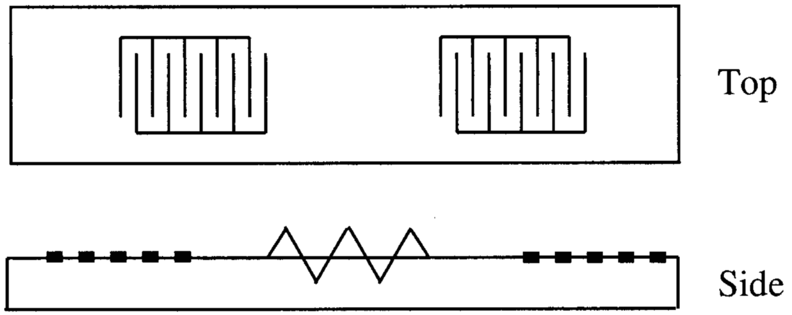
Principle: Measure the temperature at which dew or frost forms on a cold surface.

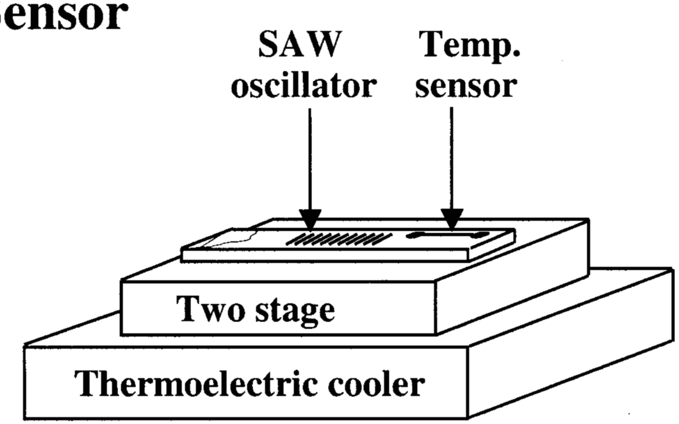
Equilibrium Water Vapor Pressure Curves from Steam Tables



Direct Dewpoint Sensor

SAW oscillator
- Rayleigh wave confined to surface
- High sensitivity to condensed water

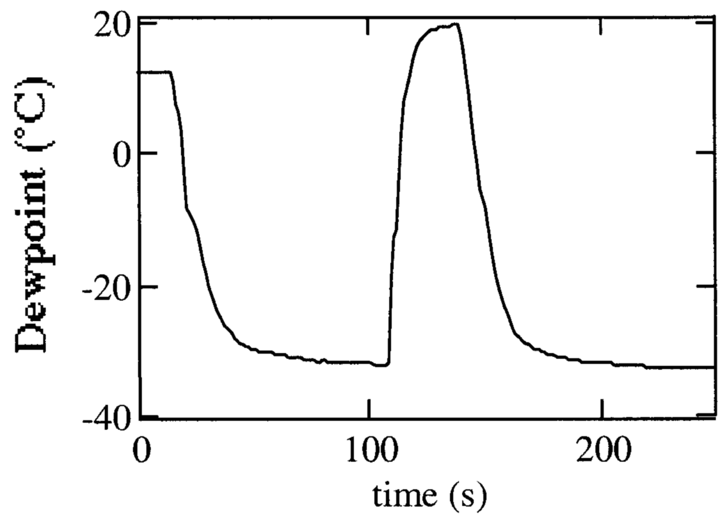




SAW oscillator as transducer for dewpoint hygrometer
- Thermoelectric cooler for electronic temperature control.
- SAW frequency is sensitive to water/ice condensation.
- Frequency vs. temperature slope changes at dewpoint
- Feedback control permits continuous dewpoint measurement.

Advantages of SAW hygrometer
- Compact design
- Fast response
- Wide dynamic range
- Frequency signal —> low noise
- Dewpoint is a fundamental thermodynamic quantity —> inherently accurate

SAW - fast response to humidity transients

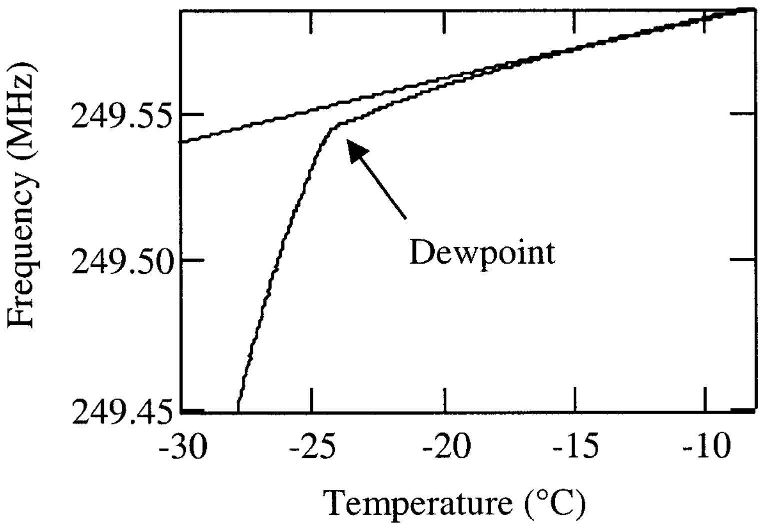


Cooling the SAW in the Presence of Water Vapor

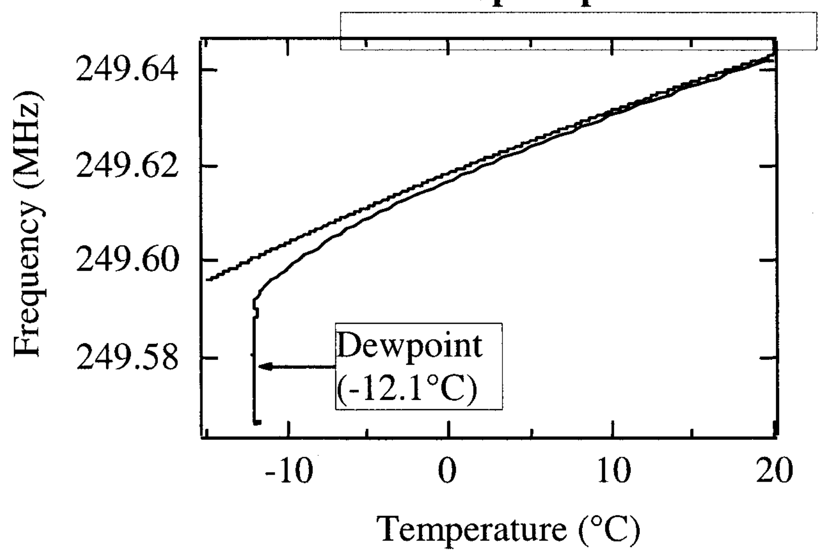
Transducer Response to Condensation

Water/frost accumulation = Decrease in SAW frequency

Open Loop Response



Closed Loop Response



Cooling SAW in presence of water vapor

- TEC current under open loop control, independent of frequency;
- Sharp change in slope at dewpoint/frostpoint; slope depends on conditions and ramp rate;
- Relatively slow - one measurement per cycle.

Feedback control

- TEC current under closed loop control, tied to frequency;
- At equilibrium, temperature = dewpoint/frostpoint, depending on water phase;
- Fast response.

Surface Acoustic Wave Hygrometer

SAW Hygrometer

- Accurate dewpoint measurement
- 100x higher sensitivity than chilled mirror
- 10x faster response than chilled mirror

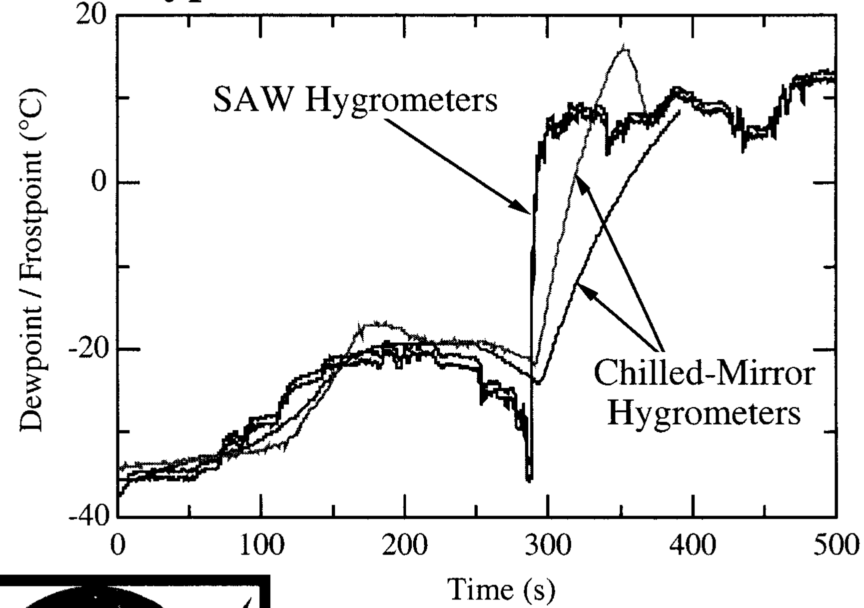
Applications

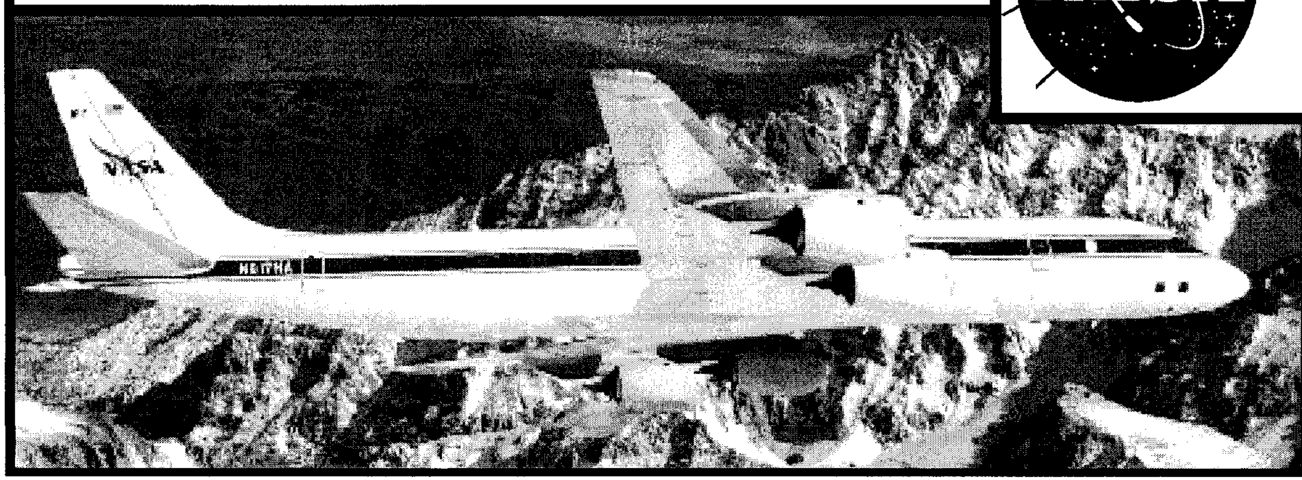
- Atmospheric humidity
  - Radiosonde balloons, airplanes, UAVs
  - Planetary landers, aerobots
- Advanced environmental monitoring

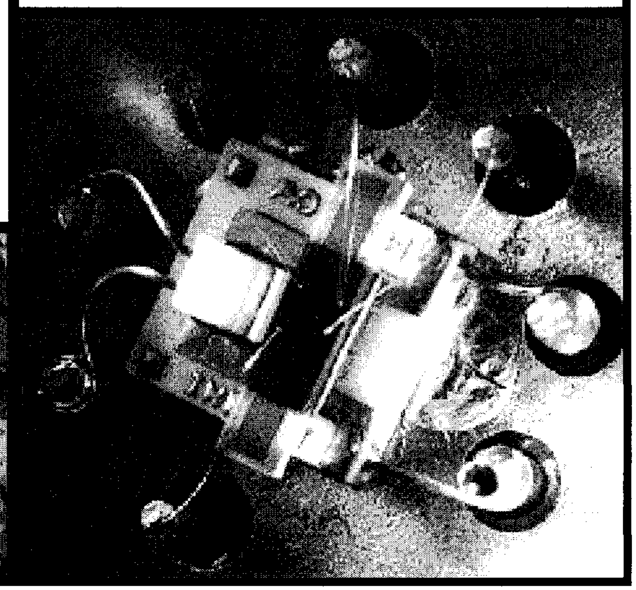
Key Challenges

- Miniaturization
- Integration
- Cost

Prototype Validation on the DC8 (1995)







JPL Radiosonde Development

Concept: Small, accurate payload for in situ atmospheric profiles.

Applications: Direct calibration of commercial radiosondes.
Ground truth for remote sensing instruments.

Validation: Flight test on radiosonde balloon.
Comparison with commercial radiosonde.

Unique Features of JPL Radiosonde:

- **SAW hygrometer**
  - Speed: Over an order of magnitude faster than state-of-the-art.
  - Sensitivity: Two orders of magnitude better sensitivity than optical dew detection.
  - Accuracy: Direct dewpoint detection for accuracy over a wide range.
- **Instrument integration (1 kg payload)**
  - Accurate sensors
  - DSP-based computer
    - Autonomous operations
    - Digital feedback control of SAW temperature
  - Spread-spectrum modem
    - High data rate
    - Network capability.
  - GPS receiver

Reference Radiosonde

Motivation

- U.S. Radiosonde Program: ~ 80,000 launches/year
  - Most comprehensive and widely available source of in situ weather data
  - U.S. Weather Service relies on radiosonde data for weather prediction
  - Data is not sufficiently reliable for long-term climatic studies
- Radiosonde hygrometer problems
  - Variable data quality: poor at high and low humidities
  - Data interpretation difficult: variable instruments and practices
  - Known inaccuracies

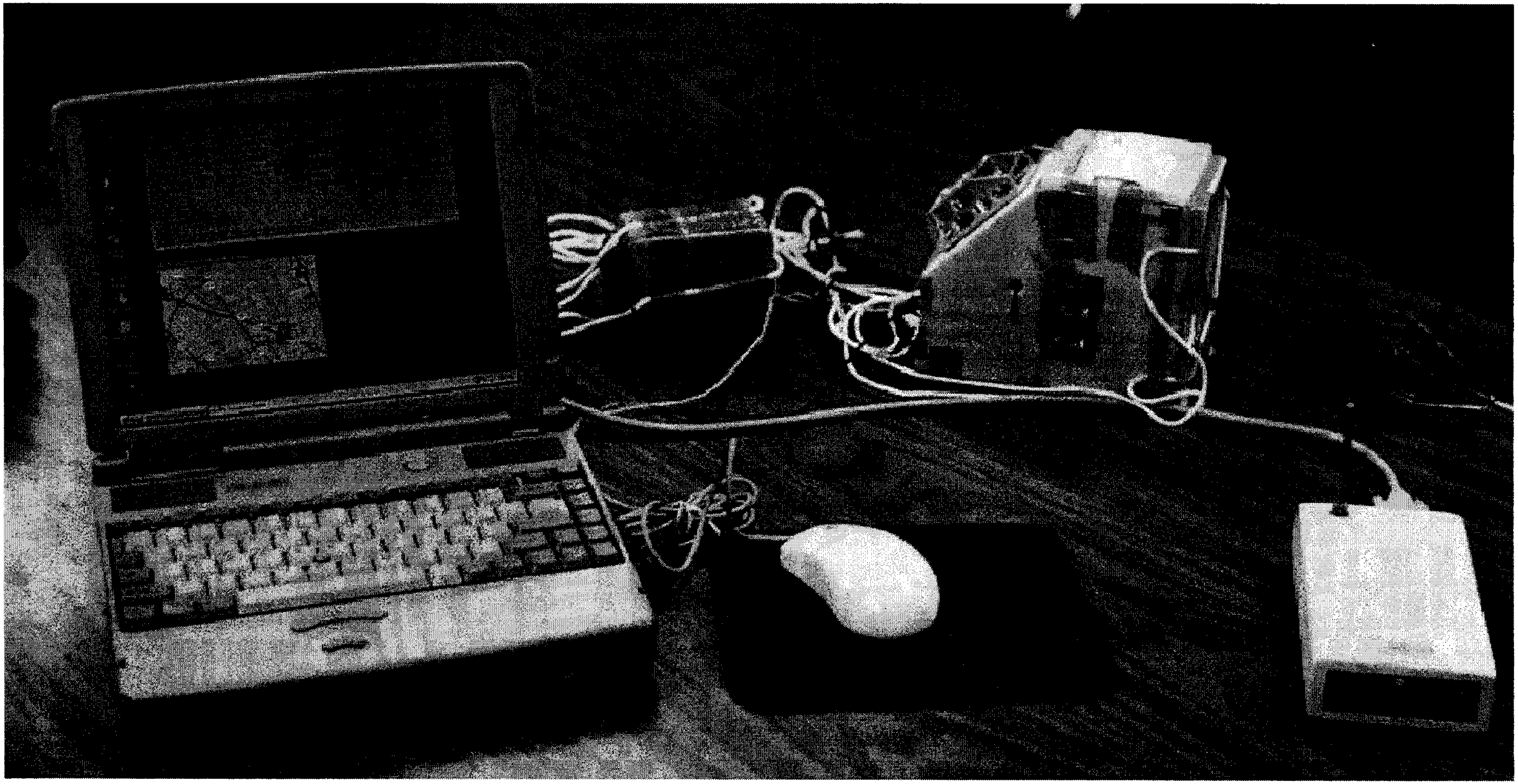
    Pacific radiosonde tests: Vaisala RH is too low.

    Ground-based measurements: Carbon hygristor RH too high.
- Radiosonde reference hygrometer does not exist

Technology challenges

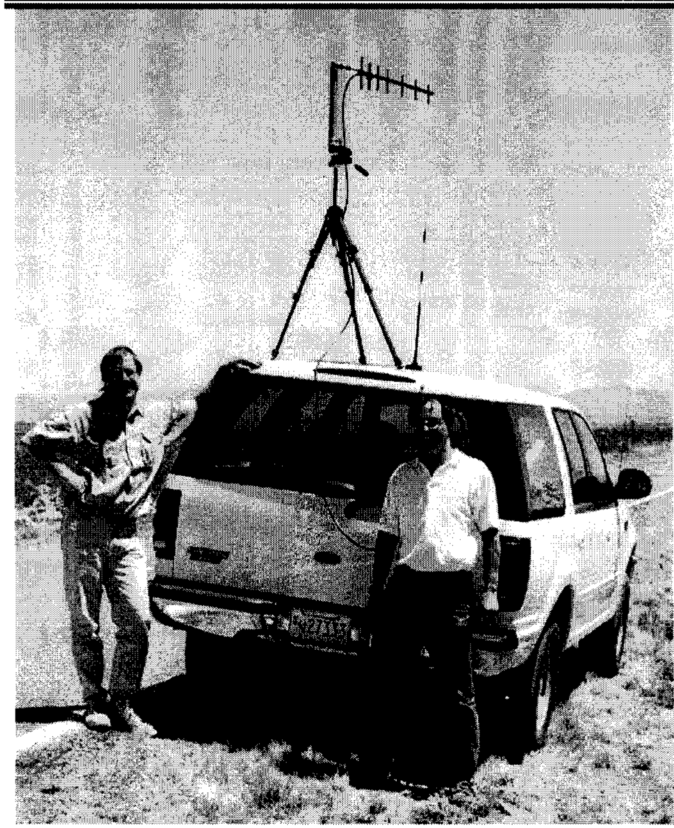
- Accuracy: Large variation in water vapor concentration and temperature.
- Integration: Balloon weight < 6 lb (2.7 kg) to meet FAA restrictions.
- Cost: Must ultimately be ~$1K or less.

JPL Radiosonde



Balloon payload and ground station hardware

Ground Support for Balloon Flight



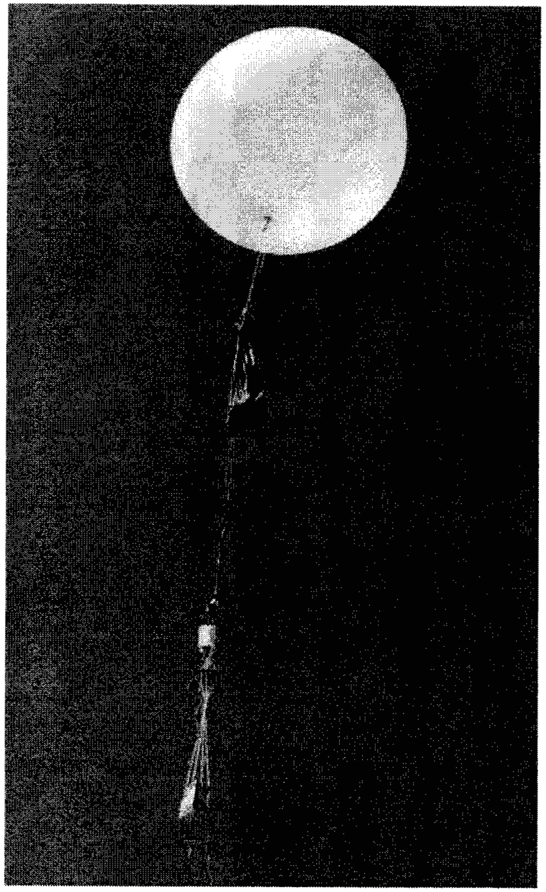
JPL chase vehicle / ground station
- Laptop computer - modem
  - Remote command / control
  - Data recording
  - **Real-time tracking**
- GPS receiver
- Battery power

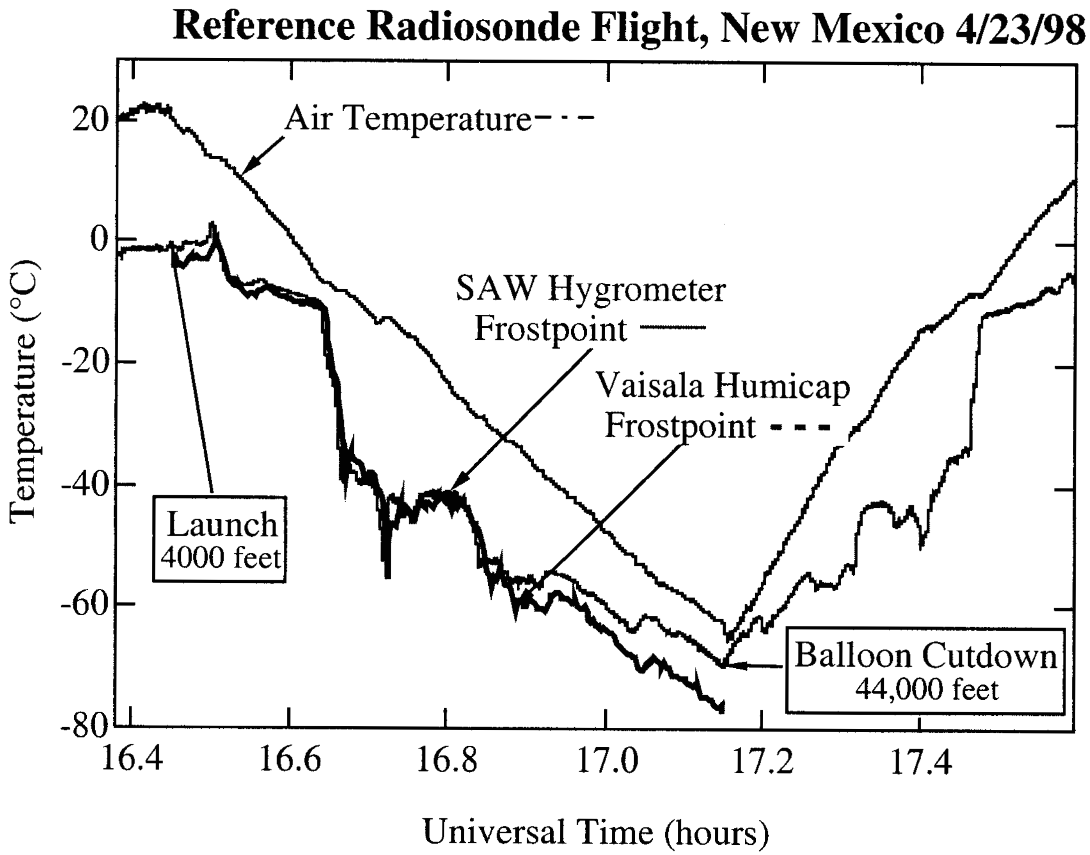
Balloon launch support
- Vaisala radiosonde ground station
- Helium tanks
- Diesel generator

JPL

Reference Radiosonde

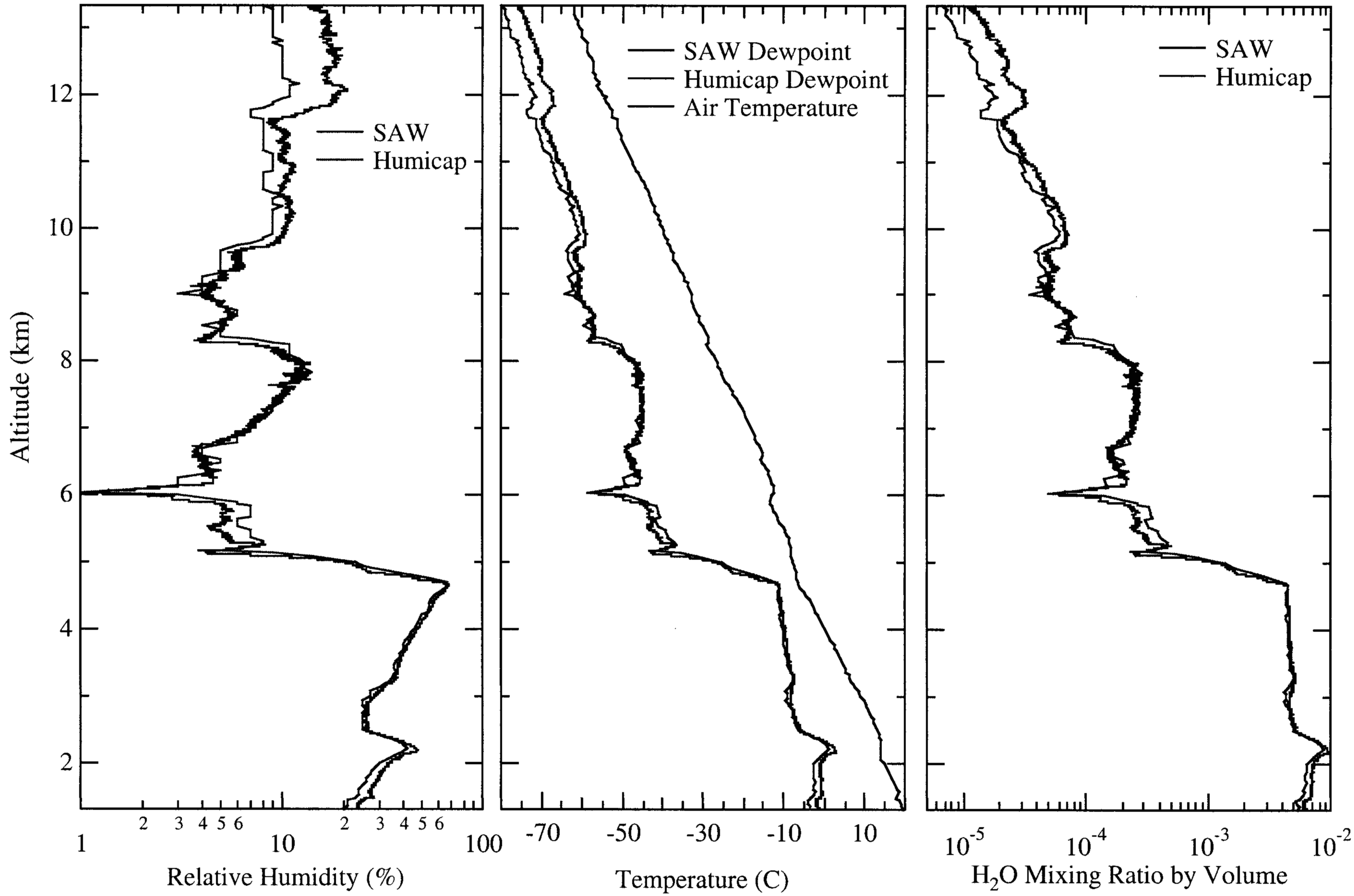
Strengthening operational in situ observational systems is a high-priority science objective for the Earth Science research theme "*Global Water and Energy Cycle*".



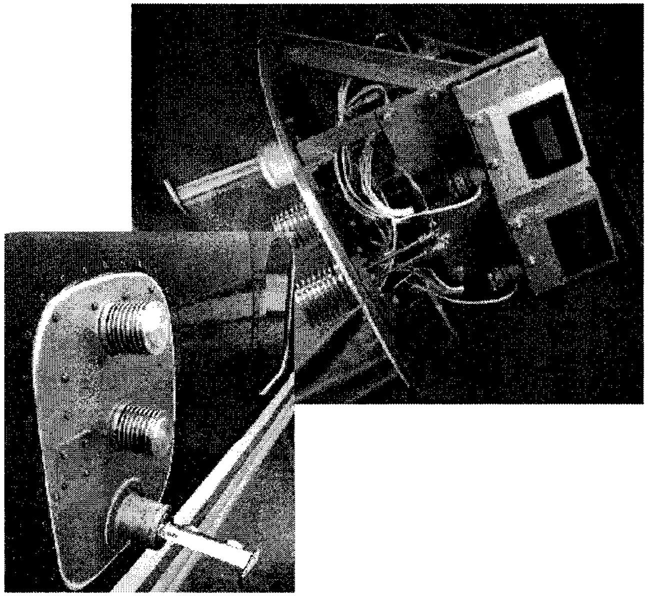


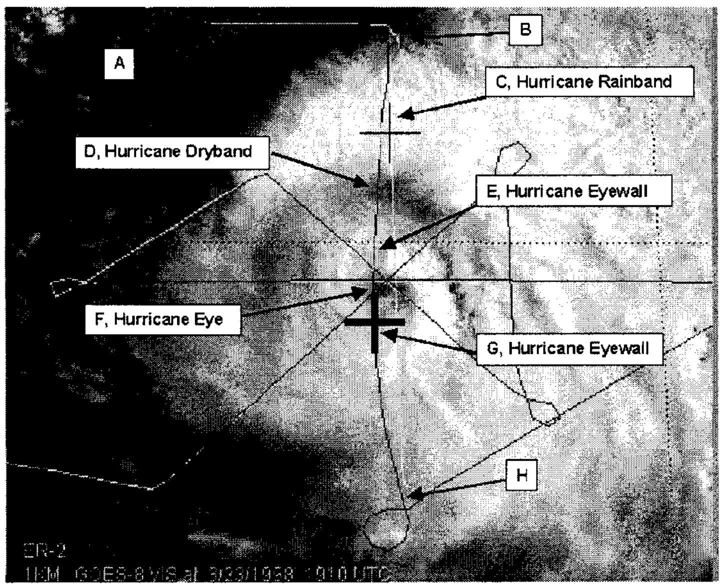
- SAW hygrometer validation: Extremely low frostpoint: -76°C at 44000 feet (6 ppm)
- The flight experiment provided a direct *in situ* comparison with Vaisala RH sensor.

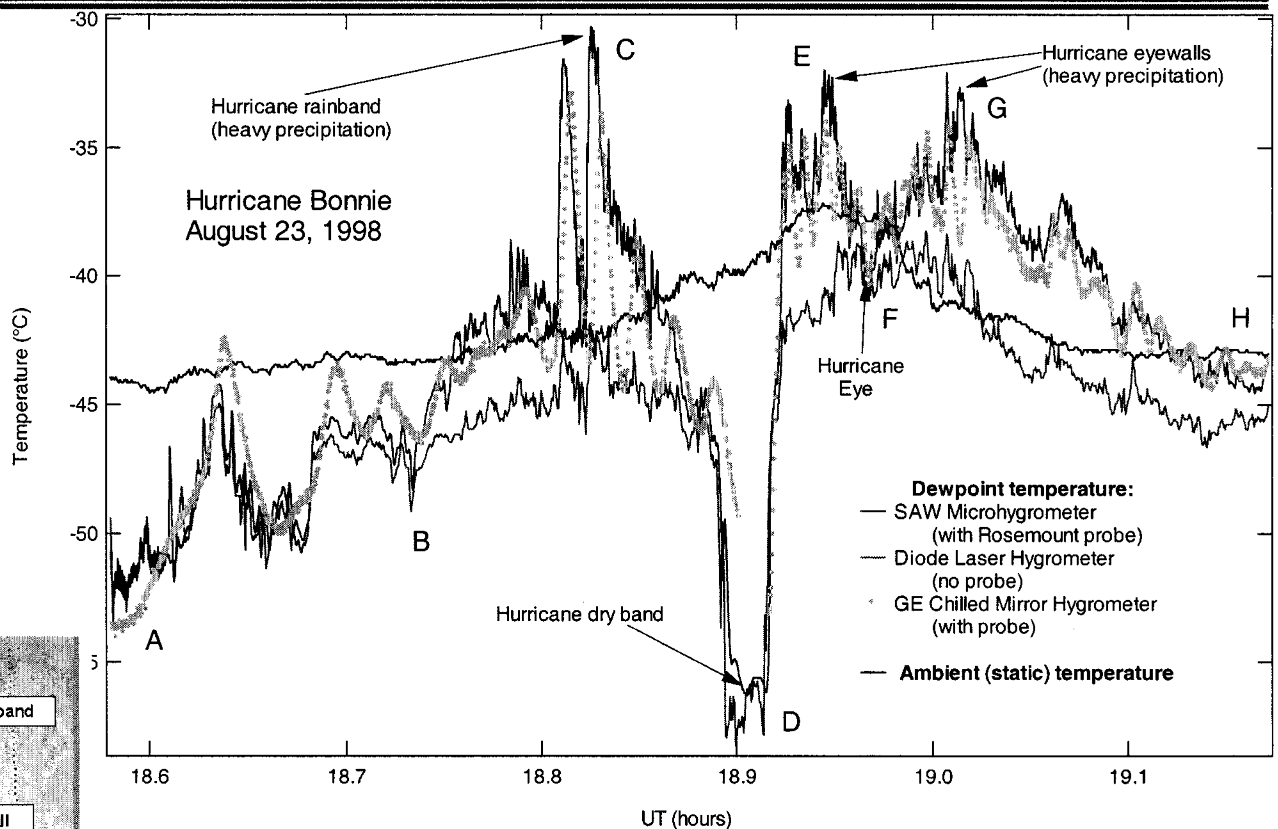
Comparison of SAW Hygrometer with Humicap



Micro Weather Station





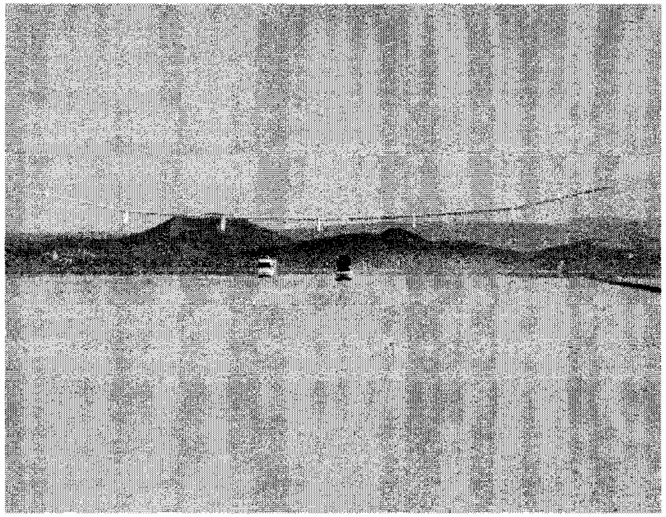


NASA's Third Convection and Moisture Experiment

In situ humidity measurements with dewpoint microhygrometer

Helios

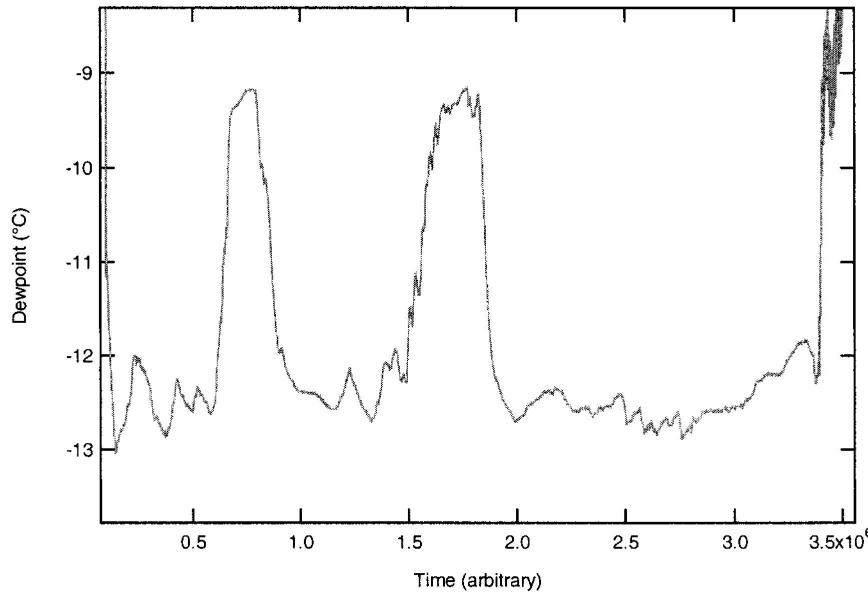
Dryden Flight Research Center EC99-45140-11 Photographed18AUG1999
Prototype of Helios solar-electric high-altitude flying wing.
NASA/Dryden Tom Tschida



Dryden Flight Research Center EC99-45285-7 Photographed DEC1999
Trailed by support vehicles, the prototype of the Helios solar-electric flying wing lands on Rogers Dry Lake to conclude its sixth flight. NASA Dryden/Tom Tschida

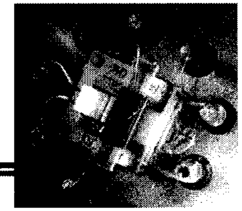
AeroVironment Helios UAV

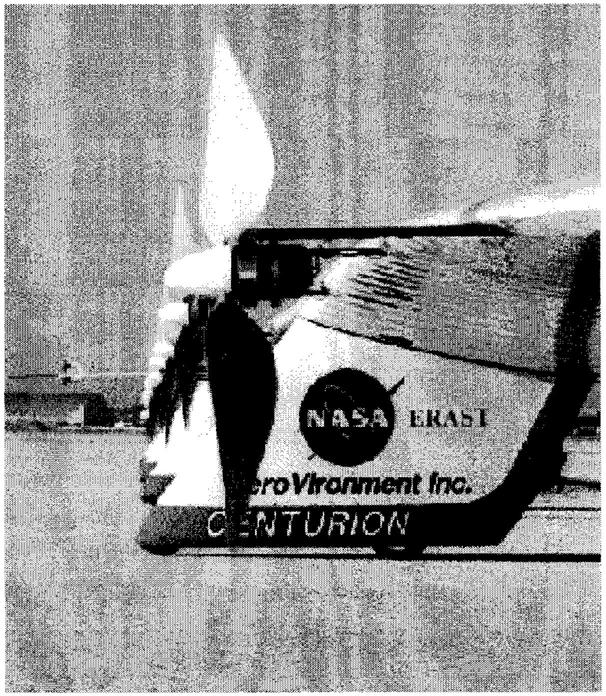
Unpiloted aircraft designed for high-altitude (100,000 ft), long-term deployment (6 months)



SAW Hygrometer dewpoint during Helios flight on Oct 13, 1999

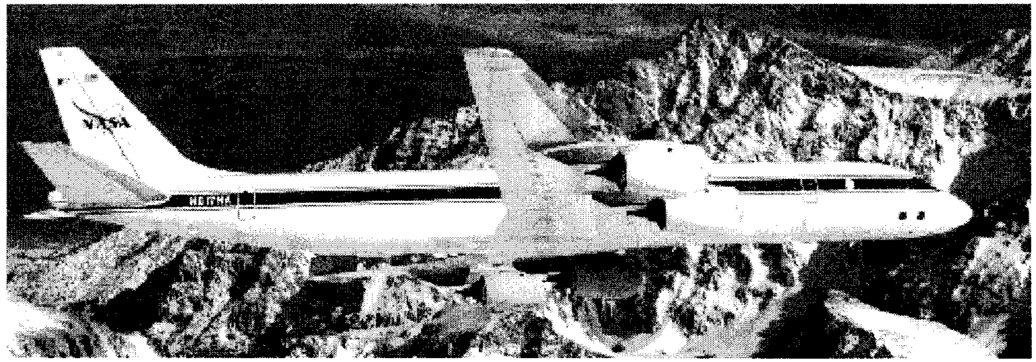
Dewpoint Microhygrometer - Future Missions





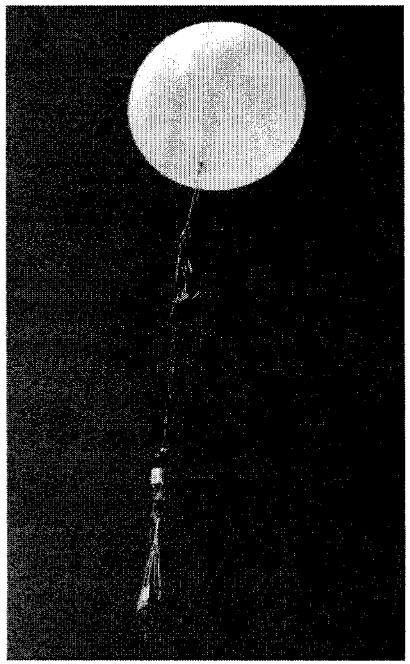
Unmanned Aeronautical Vehicles
(AeroVironment Helios)

NASA DC-8 (CAMEX-4, Crystal)



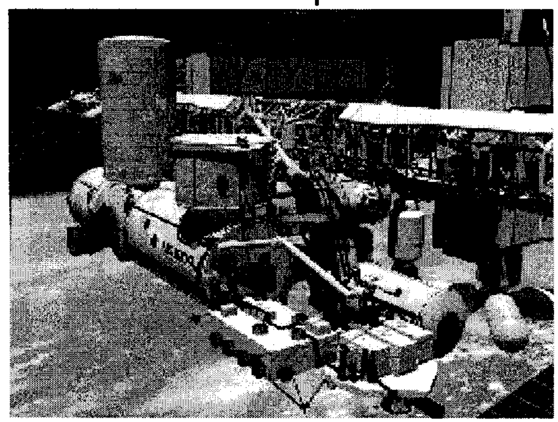
ARM
Atmospheric Radiation Measurement Program

Radiosonde Intercomparison
(AFWEX)



Reference Radiosonde
(Wallops)

Space Station



Mini/Micro *In Situ* Atmospheric Sensors

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MEMS hygrometer:	M. Pan (UCLA), H. Chien (UCLA), Bill Kaiser (UCLA)
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Radiosonde:	Kevin Watson (346), Greg Cardell (346), Doug Price (333)
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Microacoustic sensors:	Flavio Noca (346), Greg Cardell (346)
Nanoacoustic sensors:	Flavio Noca (346), Brian Hunt (346), J. Xu (Brown)

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- Space Science Enterprise - CETDP, PIDDP
- HEDS Enterprise - Advanced Environmental Monitoring Program
- JPL/Caltech - DRDF, PF

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- **Office of Earth Science - Atmospheric Dynamics and Radiation Program**
- **Office of Space Science - CETDP, PIDDP**
- **Office of Life and Microgravity Sciences - Advanced Environmental Monitoring Program**
- **JPL/Caltech - DRDF, PF**